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Furthering the Science of Ocean Climate Modelling

From Maltrud et al, page 5: Global Ocean Modelling in the Eddying Regime using POP

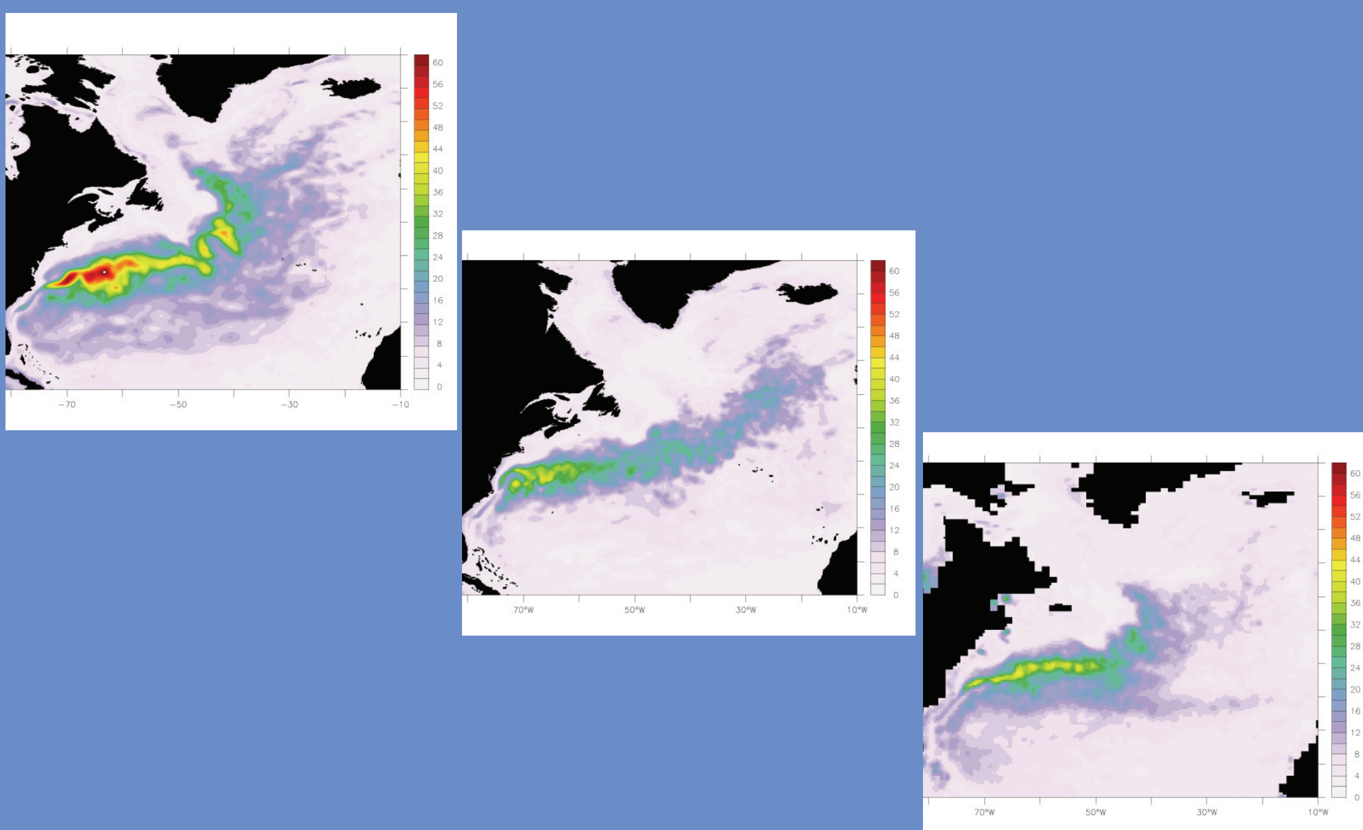

Figure 1. Sea surface height variability (cm) from a) the global 0.1º tripole, b) the global 0.1º dipole, and c) the AVISO altimeter data.

CLIVAR is an international research programme dealing with climate variability and predictability on time-scales from months to centuries. **CLIVAR** is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meteorological Organization, the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO.

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Parameterizing Submesoscale Physics in Global Climate Models

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Introduction

The ocean is vast and diverse. No computer in the foreseeable future will be able to directly handle the range of scales present in the ocean, yet small-scale phenomena may impact global ocean circulation and climate. The small-scale dynamics of the ocean surface mixed layer are an excellent example, because they are not explicitly resolved by climate models even though they mediate property exchange between the atmosphere and ocean.

The majority of studies of small scales have focused on mesoscale geostrophic eddies (typical scales of a month and 100km) or finescale waves and turbulence (typical lengths up to hundreds of meters and inertial or faster time scales). The range of scales in between the mesoscale and the finescale was considered to be of only secondary importance, perhaps just the tail of the mesoscale spectrum. However, recent work has shown that these scales, the submesoscales, have interesting dynamics and potential climate impact through their actions near the ocean surface. Limited duration ocean-only global simulations with grids fine enough to fairly represent mesoscale eddies are becoming common, e.g., Maltrud and McClean (2005). Eddy-resolving coupled climate models are expected to soon follow, but many decades remain until the submesoscale can be well-resolved in global climate models. Oschlies (2002) demonstrates that the near-surface model fidelity is significantly improved in a regional ocean-only model with 2km horizontal resolution, just brushing into the submesoscale-permitting range. Thus, parameterization of the physics at these scales would benefit modelling for decades to come.

Submesoscale dynamics are dominated by the development of fronts and the ageostrophic circulations associated with the fronts. Observations have shown that near-surface fronts are ubiquitous at all scales larger than the local mixed layer deformation radius, typically a few kilometres (Ferrari and Rudnick, 2000, Hosegood et al., 2006). Recent studies of submesoscale physics have addressed various aspects of frontal dynamics: wind-front interactions (Thomas, 2005), frontogenesis (Lapeyre et al. 2006, Capet et al. 2008), and frontal instabilities (Boccaletti et al. 2007, hereafter BFF). Nice reviews of these results can be found in Thomas et al. (2008) and Mahadevan and Tandon (2006). Thomas and Ferrari (2008) compare the three effects and conclude that they are of similar magnitude for typical oceanic conditions. In all these studies a novel view of the upper ocean emerges, where the depth and stratification of the surface mixed layer is not set by the atmospheric surface fluxes, as currently assumed in all boundary layer theories and parameterizations, but it is radically modified by the ageostrophic circulations that develop at lateral fronts. Fox-Kemper et al. (2008, hereafter FFH) and Fox-Kemper and Ferrari (2008, hereafter FF) derive and validate a parameterization scheme to represent the mixed-layer restratification associated with frontal instabilities and frontogenesis. The dynamics associated with coupling between winds and fronts have not yet been cast in a parameterization.

This note introduces the FFH parameterization. It has been implemented in two global climate models: the Community Climate System Model/Parallel Ocean Program (CCSM/POP2, Smith and Gent, 2002) and the Geophysical Fluid Dynamics Laboratory Coupled Model/Generalized Ocean Layer Dynamics (CM2.2/GOLD, Delworth et al., 2006, Adcroft and Hallberg, 2006). So far, the parameterization has been tested in three contexts: 1) in idealized simulations (FFH and FF), 2) in an ocean-only, 3-degree, 100-year simulation of POP, and 3) in a 20-year 1-degree coupled ocean-atmosphere CM2.2/GOLD simulation. These tests differ greatly. POP is a z-coordinate model with the Large et al. (1994) finescale mixing parameterization, and GOLD is an isopycnal-coordinate model with a refined bulk mixed layer model (Hallberg, 2003). Nonetheless, when the missing physics of frontal instability restratification is approximated by the FFH parameterization, both POP and GOLD show a reduction in model bias when compared to control runs without the parameterization. Future papers will address in more detail the implementation and effects in these global models.

Dynamics of Mixed Layer Eddies

The weak stratification and shallow depth of the mixed layer lead to submesoscale ageostrophic baroclinic instabilities that are trapped within the mixed layer (BFF). FFH dub them mixed layer eddies (MLEs) when they reach finite amplitude. MLEs form by extracting energy from fronts. They have slightly sub-inertial time scales so are fast enough to grow even in the presence of nightly convective mixing. MLEs are submesoscale features with scales near the mixed layer deformation radius (100m to 5km). Satellite (Munk et al., 2001) and in situ (Rudnick, 2001) observations confirm that the ocean is populated with eddies with characteristics consistent with MLE.

Both mesoscale eddies and MLEs drive overturning circulations that act to slump lateral density gradients, converting steep isopycnal surfaces to shallower, wavy ones. The slumping results in a lateral mixing of tracers and in an increase of the vertical density stratification. During slumping lighter water is moved over denser water, and extraction of potential energy results. BFF and FFH show that the slumping and restratification by mixed layer instabilities quickly outpaces restratification by Rossby adjustment (Tandon and Garrett, 1994) and other instabilities (see also Haine and Marshall, 1998).

Since Taylor (1921), eddy diffusivities have been the basic tool to approximate stirring by eddies. Gent and McWilliams (1990, hereafter GM) showed that a similar approach can be taken to represent mesoscale ocean eddies, as long as the lateral diffusion of buoyancy is accompanied by a vertical buoyancy flux acting to release potential energy (e.g., Green, 1970). An eddy-induced velocity streamfunction (see Griffies, 1998, for implementation) can be used to slump density gradients, hence: releasing potential energy and also transporting buoyancy down its mean horizontal gradient to achieve lateral mixing.

FFH follow GM in introducing an eddy-induced overturning streamfunction, but instead of scaling this streamfunction to produce known horizontal mixing (the GM transfer coefficient), they derive a scaling for the streamfunction that achieves the expected release of available potential energy and hence eliminate any dependence on unknown transfer coefficients. The scaling was then tested against a suite of high resolution numerical simulations. The choice to focus on vertical fluxes was motivated by the fact that MLEs rapidly restratify the surface mixed layer through vertical exchanges of buoyancy, while lateral fluxes associated with MLEs are dominated by larger scale motions. Also, it was observed during spin-down of mixed layer fronts by MLEs that the vertical flux is nearly constant while the horizontal flux and diffusivity change dramatically in time. FFH parameterize the submesoscale eddies only, so the parameterization is intended to be used in mesoscale-resolving simulations or in conjunction with a mesoscale parameterization (e.g., GM or a recent improvement, e.g., Ferrari et al., 2008).

The FFH parameterization is cast as an expression for the overturning streamfunction at a front:

$$\mathbf{\Psi} = C_e \frac{H^2 \nabla \bar{b}^z \times \hat{\mathbf{z}}}{|f|} \mu(z)$$

Where H is mixed layer depth, $\bar{b}^z$ is the buoyancy averaged over the mixed layer depth, f is the Coriolis parameter and the structure function is

$$\mu(z) = \max\left\{\left[1 - \left(\frac{2z}{H} + 1\right)^2\right]\left[1 + \frac{5}{21}\left(\frac{2z}{H} + 1\right)^2\right], 0\right\}$$

The streamfunction gives an eddy-induced velocity associated with the overturning:

$$\mathbf{u}^* = \nabla \times \mathbf{\Psi}$$

which is used to advect buoyancy and other tracers. The parameterization approximates the eddy fluxes:

$$\overline{\mathbf{u}'b'} \approx \mathbf{\Psi} \times \nabla \bar{b}$$

The form of the parameterization guarantees a down-gradient horizontal flux and an upward, restratifying vertical flux. The scaling found for mixed layer fronts extends to cover the regime of restratification after deep convection, by reproducing the scalings found by Jones and Marshall (1993, 1997) and Haine and Marshall (1998).

Implementation and Impact in Global Climate Models

In a global climate model, the parameterization must be modified. A useful form is,

$$\mathbf{\Psi} = C_e \frac{H^2 \nabla \bar{b}^z \times \hat{\mathbf{z}}}{\sqrt{f^2 + \tau^{-2}}} \mu(z) \frac{\Delta x}{L_f}$$

Introducing the timescale τ, for mixing momentum across the mixed layer (typically a few days) makes the parameterization converge to the subinertial mixed layer approximation (Young, 1994) near the equator. Also, differentiability and finite amplitude are preserved as f goes to zero. The ratio of the grid resolution Δx to the typical scale of mixed layer fronts L_f preserves the average vertical buoyancy flux in the face of weaker buoyancy gradients in coarse-resolution models, which are assumed to have a white spectrum as in models and data (Hallberg & Gnanadesikan, 2006 and Ferrari and Rudnick, 2000). The frontal scale may be either a fixed number, e.g., 5 km, but observations suggest the mixed layer deformation radius (Hosegood et al. 2006).

Since the MLEs tend to restratify the mixed layer, it is not surprising to find that the boundary layer thickness is reduced when the parameterization is introduced (Figure. 1, page 19). Furthermore, the action of the parameterization is most pronounced where mixed layers are deep and horizontal buoyancy gradients are large. These regions are those anticipated by FF by inference from satellite data. The models show qualitatively similar shoaling of the boundary layer in similar regions, but quantitatively different responses to the parameterization. It is likely that the different resolutions of the models contribute significantly, and possibly also the ocean-only versus coupled configurations. In any case, once longer and more directly comparable resolutions and simulations are available a more detailed comparison will follow.

Is a shallower boundary layer or mixed layer more realistic? The POP model provides mixed layer depth as well as boundary layer depth. Figure. 2 shows a comparison to mixed layer climatologies of the time average of the mixed layer depth for years 90-100 of the POP model simulation with the MLE parameterization and the control run without. BMFLI is the de Boyer Montegut et al. (2004) temperature-based mixed layer climatology and Levitus is the Monterey and Levitus (1997) climatology. Figure. 2 shows a probability distribution of finding a given difference between the model time-mean and the climatology at an arbitrary location. It is clear that the change induced by the parameterization is larger than the difference between climatologies, and that the control run is biased toward deep mixed layers. Introducing the parameterization reduces this bias: the rms error is reduced from about 15m to 7m, and the skewness (indicating bias) is reduced from 2.4 to 0.6.

Conclusions

A new parameterization for restratification by mixed layer eddies is introduced. The parameterization was shown to be effective in idealized simulations by FFH and FF. It has now been included in CCSM/POP and CM2.2/GOLD and this note demonstrates that it reduces bias over control runs in preliminary simulations.

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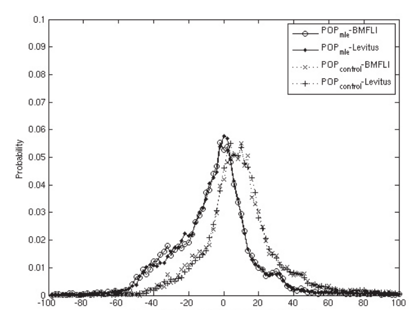

Fig. 2: Probability distributions of difference between modeled time-mean mixed layer depth and observed time-mean mixed layer depth. POP model with MLE parameterization and the POP control run are compared to BMFLI and Levitus mixed layer depth climatologies. (Bin width of 2m).

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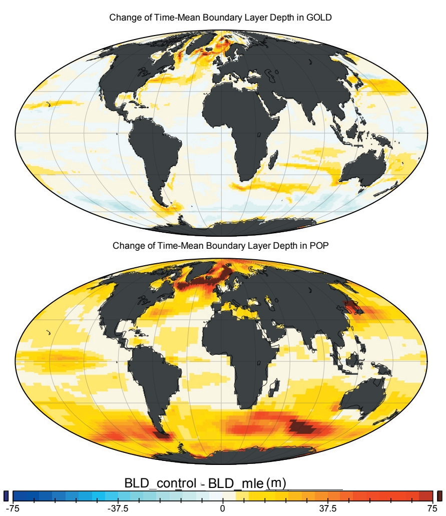

Fig. 1: Reduction in boundary layer thickness with the introduction of the MLE parameterization in GOLD (upper) and POP (lower). The average over the last ten years of the simulations are shown. The boundary layer is the layer over which finescale mixing due to winds and convection is active. Generally, it is less than or equal to mixed layer depth.